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Development and experimental study of beryllium window for ITER radial X-ray camera

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HIGHLIGHTS

- The thickness of the beryllium foil is chosen as 80 μm to guarantee its safety under high pressure differential in accident events.
- Using low purity of beryllium as the transition material, the effect of thermal stress caused by diffusion bonding process can be reduced.
- Sealing ring and honeycomb-like supports are designed and used in the mechanical clamped beryllium window to enhance its sealing and safety performance.
- The beryllium windows have good performance under severe working conditions like high temperature baking, vibration or impact load.

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ABSTRACT

Radial X-ray camera (RXC) is a diagnostic device planned to be installed in the ITER Equatorial Port #12. Beryllium window will be installed between the inner and outer camera of RXC, which severs as the transmission photocathode substrate and also the vacuum isolation component. In this paper the design and manufacture process of two types of beryllium windows were introduced. Although 50 μm thickness of beryllium foil is the best choice, the 80 μm one with X-ray threshold of 1.34 keV was selected for safety consideration. Using the intermediate layer (low purity of beryllium) between the beryllium foil and the stainless steel base flange is an effective strategy to limit the welding thermal deformation and thermal stress of the thin foil caused by bonding between different materials. By using ANSYS software, the feasibility of the aperture design was analyzed and validated. Metal sealing ring was applied in the mechanical clamped beryllium window for its good stability under high temperature and neutron radiation. Although both of the hollow metal sealing ring with 0.03 mm silver coating and the pure silver sealing ring can satisfy the sealing requirement, the later one was chosen to produce the final product. Two hours 240 °C high temperature baking test, two hours 3.3 Hz vibration test and fatigue test were performed on the two types of beryllium windows. Based on the tests results, the two types of beryllium windows could stand the high temperature baking during the wall conditioning phase of ITER tokamak and the vibration during transportation without causing large leakage. Both of the two types of beryllium windows could bear impact load (0.1 MPa pressure difference) for many times without failure.

1. Introduction

Radial X-ray camera (RXC) is one kind of diagnostics which will be applied and arranged on Equatorial Port #12 of ITER tokamak. The ITER RXC is designed to measure the poloidal profile of the plasma X-ray emission with high spatial and temporal resolution [1]. In order to enhance the maintainability of the diagnostics on the port, all of them are installed in a port plug which can be assembled or disassembled easily. There are three vertical drawers in the Port #12 plug and the RXC located in the middle one. With the "drawer" design of the port plug, the diagnostics including the RXC can be maintained separately by remote handling device which also provide an upgrade path for future advanced detectors. ITER RXC has two main components: the inner camera which is installed in the vacuum vessel (VV) of ITER and the outer camera [1,2]. The inner camera and the big flange are cooled by cooling water system to remove the heat load generated by nuclear radiation. The interfaces of the inner camera and the outer camera are beryllium

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windows which are two Knife-edge flanges with beryllium foils on them. For safety consideration, the outer camera is pumped to a secondary vacuum (about 10^{-2} Pa) to reduce the pressure difference of the two sides of beryllium window. In addition to optical component the beryllium window also acts as vacuum isolation component.

The key optical function of the beryllium window is X-ray transmission; the X-ray transmission threshold which is the minimum energy of the X-ray to penetrate the beryllium filter should be as low as possible. Besides, the safety of the beryllium window is another critical issue related to its design. The failure of beryllium window can cause serious consequences, such as the rapid increase of the gas pressure in VV and the neutron diffusion from the inner camera to the outer camera. The design requirements of the ITER beryllium window are summarized as follows: the X-ray transmission threshold of the window should be 1 keV; reliable support with acceptable light-blocking area; good sealing performance with leak rate less than 6×10^{-10} Pa m^3 s^{-1} during normal operating phase; bearing impact load with one atmospheric pressure difference many times and static load of 0.2 MPa pressure difference without causing broken or excessive leakage; easy to be manufactured, fabricated and maintained.

2. Engineering design of beryllium window

2.1. Bonding method consideration of beryllium window's assembly

Just like the beryllium windows used on other equipments, the ITER RXC beryllium window has a structure base (CF-150) made by SS316L, the thin beryllium foil is fixed in the middle of it. Epoxy bonding, brazing and diffusion bonding are three common methods to connect the foil with the substrate material of the base. Using epoxy as bonding material can simplify the manufacture process of the beryllium window, but as a critical component used on fusion reactor which is baked under high temperature (240 °C in the outgas process) and working in the condition of high dosage of neutron radiation which can reach to $3 \times 10^9\ n/\text{cm}^2\ \text{s}$ in D–T operating phase [2], the epoxy is not stable in those situations. Vacuum brazing has been performed successfully on the beryllium window for CESR-C (Cornell Electron-Positron Storage Ring) [3]. There are two vacuum braze steps on it: two stainless steel tubes which were brazed to each end of a copper ring at 955 °C with BAu-4 (82%Au–18%Ni) alloy wires, then the 75 μm thick beryllium disk is vacuum brazed onto the copper ring using Bag-18 (60%Ag30%Cu10%Sn) alloy at 719 °C [3]. One of the big challenges of the window's assembly when beryllium foil is being brazed onto the substrate, however, is the coefficient difference of thermal expansion caused by different materials, and during cool down from brazed temperature the thin foil would become pre-stressed [4,5]. Extreme care must be taken to avoid sudden pressure changes cross the window aperture, either during the pumping or venting process to atmosphere pressure. Diffusion bonding is an available method for different types of materials' bonding. Under a temperature of 70% of the material's melting point and apply pressure on the workpieces, the two parts will be connected by the process of atomic diffusion. The material properties of the bonding joint changed slightly after diffusion bonding process. In the R&D phase, one diffusion bonded beryllium window was designed and manufactured successfully. Besides, a new type of beryllium window called mechanical clamped beryllium window on which the sealing ring was used to realize vacuum tight has also made significant progress.

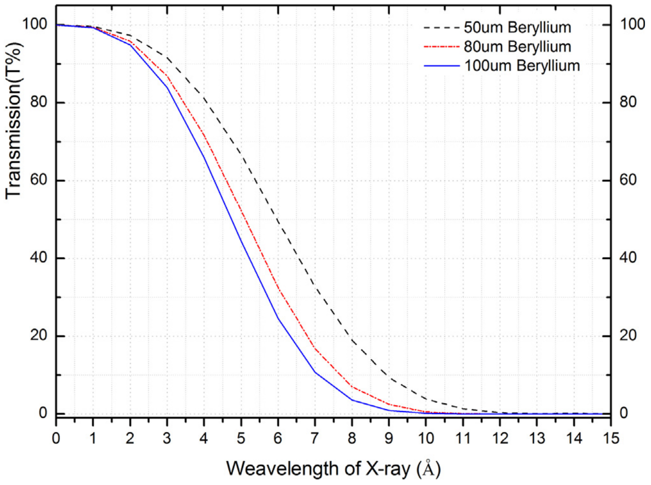

Fig. 1. Transmittance of beryllium foils with different thicknesses.

2.2. The thickness selection of the beryllium filter

Thick beryllium foil benefits to the beryllium window's safety under high pressure, meanwhile, such a window strongly absorbs soft X-ray, which limits the sensitivity of the diagnostic device [6]. The effective energy range of X-ray measured by ITER RXC is from 1 keV to 200 keV with the wavelength of 12.4–0.062 Å [2]. The transmittance of the beryllium filters with three different thicknesses was studied as Fig. 1 shows. 50 μm thick beryllium foil has the X-ray threshold of 1 keV and can meet the function requirements perfectly. Taking the strength and safety into consideration, the 80 μm thick beryllium foil was selected finally.

2.3. Engineering design of two types of beryllium windows

Two types of beryllium windows based on different connection methods were designed and manufactured during the R&D process. For the brazed one, a transition part made by low purity of beryllium was added to decrease the welding stress remained in the beryllium foils; dividing the big aperture into small ones can strengthen the beryllium foils to stand high pressure differential. For the mechanical clamped window, by applying the metal sealing ring, good vacuum sealing performance was realized; special support was designed to prevent the large deformation of the foil under high pressure which can improve its safety performance.

2.4. Structure design and analysis of the diffusion bonded beryllium window

2.4.1. Aperture size design

The aperture that the ITER RXC needs is a rectangle whose size is 60 mm × 25 mm. Big aperture is benefit to improve the light transmittance of the window, however, big aperture can cause big deformation of the beryllium foil in the middle area and also cause extra high stress concentration at the edge region. Big deformation and high stress increase the risk that the beryllium window would be destroyed when being exposed to high pressure. Adding auxiliary supports (bars) is a useful method to strengthen the beryllium foil which can prevent it from large deformation and also cut down the light transmittance of the RXC accordingly. In the design of ITER RXC beryllium window the light transmittance is required larger than 0.7. In order to find the best solution of the aperture size for beryllium window support design, ANSYS software was used for stress simulation.

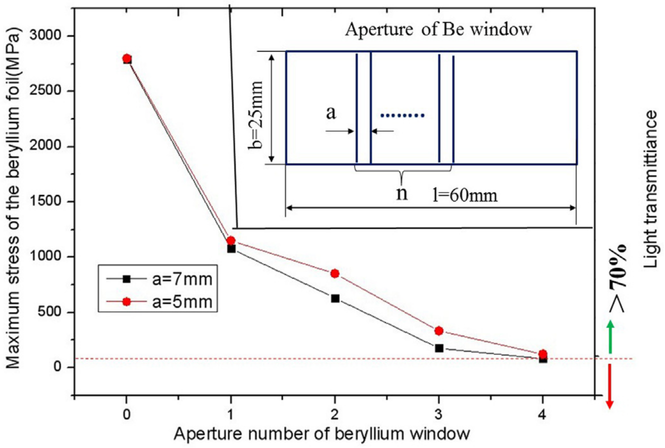

Fig. 2. Analysis of beryllium foil with different designs of support.

As a structural metal, beryllium has unique properties, it has a low density (1850 kg/m^3) and the high elastic modulus (303 GPa) [7]. In the welding process, the foil will be attached and bonded with the bars and widen the bars can reduce the processing difficulty. Based the size of the ITER RXC, two options of the width of the bars were chosen as the study objects. Based on the analysis result as Fig. 2 shows, as the bar number (n) and the width of the bars (a) increased, the maximum stress of the foil decreased. The beryllium foil (IF-1, 99.8% pure Be) used in the window was produced by Materion Brush company of US (www.materion.com), and it cannot be characterized for its mechanical properties but the ultimate stress of 350 MPa and yield stress of 207 MPa are typical for stress evaluation. Three bars which can divide the 60 mm × 25 mm window aperture into four identical ones are necessary to ensure the safety of the thin beryllium foil when being exposed to 1 atm pressure. In the mechanical analyses, the edges of the beryllium foils which are attached with the supports are fixed to simulate the welding; 1 atm pressure is applied on the top surface of the foil while the pressure load on bottom surface is zero to simulate the fault using condition. Under the above circumstances the maximum stress are 125 MPa (a = 5 mm) and 82.7 MPa (a = 7 mm), all the stresses are lower than the material's yield stress. Compared with the narrow one the light transmittance of the wide beryllium window is decreased from 83% to 77%. At last a = 5 mm was chosen to use in the R&D process to get a higher utilization rate of the aperture.

2.5. Welding structure and process design

Compared with fusion bonding like vacuum brazing, the welding process of diffusion bonding is quite gentle, however, the low compatibility of the beryllium and stainless steel materials and their difference of linear expansibility result in the difficulty of their bonding connection. Those difficulties include material annealing, thermal stress and formation of intermetallic compounds. At room temperature beryllium and SS-316L have the thermal expansion coefficient of 11.6 μm/K and 16 μm/K [8,9]. At a high temperature, the two materials are jointed, the volumes are stress free, but when the joint is cooled to the room temperature the SS-316L shrinks faster than the beryllium, creating a complex stress profile including a complex bending movement and a severe stress concentration at the joint interface. In addition, attaching and bonding the beryllium to stainless steel directly could generate brittle inter-phase and the crack in bonding zone. Based on the study and experiments, the joint strength that bonding the beryllium to the SS-316L is less than 50 MPa [10]. All of the above reasons lead to many times failure of the thin beryllium foil in the pressure-tight test during the R&D process. The general method to deal with this problem is using intermediate layer between beryllium and stainless steel to avoid the formation of brittle intermetallic. In this study the width (a) of the auxiliary supports (bars) is designed as 5 mm, and each of the 5 mm bars attaches two beryllium foils. As the surround area of the beryllium foils left for bonding is only 2.5 mm wide, inserting intermediate layer raising the risk of the bonding joints' defect and also complicating the weld process.

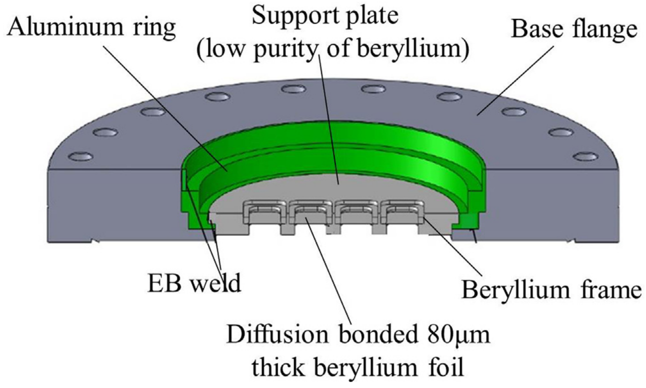

Fig. 3. Section view of diffusion bonded beryllium window.

Fig. 3 shows the final design of the diffusion bonded beryllium window, the beryllium (PF-60) which has a low purity of 99% was chosen as the transition material. Basically, the diffusion bonding process can be divided into two phases: the prepare phase and the connection phase. In the prepare phase the beryllium foils, frames and the support plate were polished and cleaned by hydrochloric acid solution, which can remove the oxide layer on the bonding surfaces and improve the quality of bonding surfaces' contact. The four thin beryllium (80 μm) foils were inserted into the grooves on the support plate firstly, which have the same shape with the foils, and then pressed the four beryllium foils with four beryllium frames.

There are three kinds of diffusion bonding which are commonly used in engineering: vacuum diffusion bonding, phase transformation super plastic diffusion bonding and HIP (hot isostatic pressing) diffusion bonding [10]. As beryllium can be oxidized easily under high temperature, vacuum diffusion bonding is applied in this beryllium window's design. Temperature is the most important parameter for the diffusion bonding process, and high temperature benefits the atomic diffusion velocity and enhances the joint strength to some extent. The temperature between 0.5 T_m and 0.8 T_m (T_m is the melting point of the beryllium material) is available and it was found that beryllium shows grain coarsening above roughly 850 °C [8], so 700–800 °C is the best choice. Additional pressure was exerted by using special designed clamps on the frames during the bonding process; after that, the beryllium support plate, beryllium foils and the beryllium frames were bonded together under high temperature, the whole volume would be cooled to room temperature with the furnace. The last step of beryllium's manufacture was to weld the support plate to the base flange. An aluminum ring was inserted between the beryllium plate and the stainless steel base flange, and electron beam welding was used to connect them. Before the final manufacture and assembly of the beryllium window, some mockups were made and some proof tests were carried out to validate the processing parameters (Fig. 4). For 50 μm beryllium window after the beryllium foils were brazed on the beryllium plate (four apertures), damage generated at the bonding interface, during the following leak test, the beryllium foils were broken along the fragile welding joints. For one of the 80 μm beryllium windows (four apertures), the beryllium foils can stand 1 atm pressure but one of the four apertures had 3 × 10^{-8} Pa m^3 s^{-1}

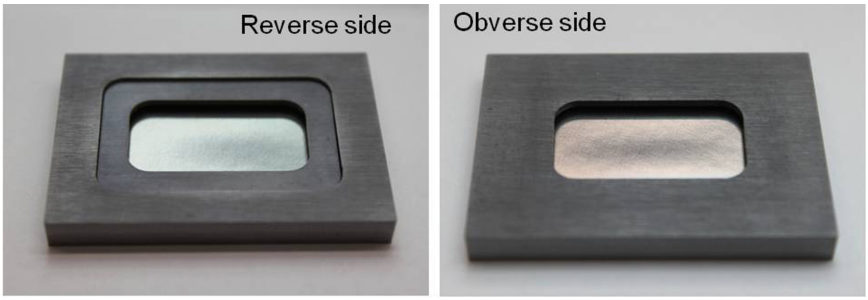

Fig. 4. Mockup of diffusion bonded beryllium window (one aperture, 80 μm).

range leakage. Another 80 μm beryllium window was assembled successfully whose leak rate was less than 6×10^{-10} Pa m^3 s^{-1}.

2.6. *Design and analysis of the mechanical clamped beryllium window*

2.6.1. *Supporting structure design*

Mechanical clamping is an advanced method which was applied in the R&D process of beryllium window in ASIPP. Sealing ring was used to isolate the different vacuum of the two sides of the window and had showed a good performance for vacuum tight. Compared with the bonded beryllium window the clamped one has the obvious advantages in the following aspects: excellent property of maintainability which can be disassembled and reassembled easily; high utilization rate, and by replacing the beryllium foil with different thickness ones, the beryllium window can be applied in different occasions or different devices; this connection method can minimize the injury of the beryllium foil in the edge area when being connected to the stainless steel. Minimizing the size of apertures and guaranteeing the light transmittance at the same time is the criterion for the support design. The main parts of the window are shown in Fig. 5 which includes the plate (with a 2.5 mm depth groove), the base flange (with a 5 mm height lugs) and the beryllium foil. In the assembly procedure the beryllium foil was positioned into the groove of the plate and then the combined body was connected with the base flange by twelve bolts, after the assembly the groove and the lugs were matched and the beryllium foil was sandwiched between the two parts. The groove and the lugs act the role of supports and they can restrain large deformation of the beryllium foil when being pressed by gas pressure.

The supports were designed as honeycomb-like type on which many little holes were arranged. In order to improve the machinability of the supports, the shape of the hole was designed into circle whose diameter is 4 mm and the minimum space between holes is 0.5 mm. All of the holes' centers were placed at the vertexes of regular hexagons, which can guarantee the area of apertures as big as possible.

The supporting effect of the honeycomb-like supports was validated by using ANSYS software in which the safety of the beryllium foil when bearing 0.1 MPa pressure difference was simulated. The maximum deformation occurred at the center of the hole and its value is 0.004 mm. The stress concentration happened at the edge of the hole, and the maximum stress of the beryllium foil is 73 MPa which is quite smaller than 350 MPa. Based on the analysis results, by preventing the beryllium foil from big deformation under high pressure, the honeycomb-like supports can keep the foil in a safe condition. Removing the burr on the edges of the holes and using a smooth transition in the edges are effective ways to improve the stress concentration phenomenon.

2.7. *Sealing structure design*

Sealing ring is well used in vacuum engineering for its good performance of vacuum tight and manufacturing. Considering the rigorous environment where the ITER beryllium window will be installed and commissioned (long time of high temperature baking, high dosage of neutron radiation), metal sealing ring rather than rubber ring was applied to the ITER RXC beryllium window design. The sealing structure and the shape of sealing ring are shown in Fig. 6. In the assembly process, the sealing ring was installed into the seal groove on the base flange, and then the beryllium foil attached to the plate was pushed by the plate to press the sealing ring. After the assembly was finished, two sealing surfaces were formed: the interface between the sealing ring and the underside

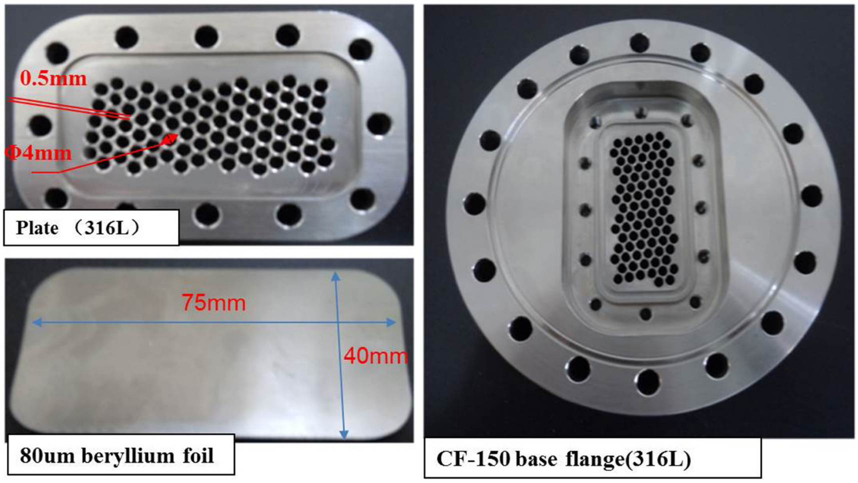

Fig. 5. Main parts of the mechanical clamped beryllium window.

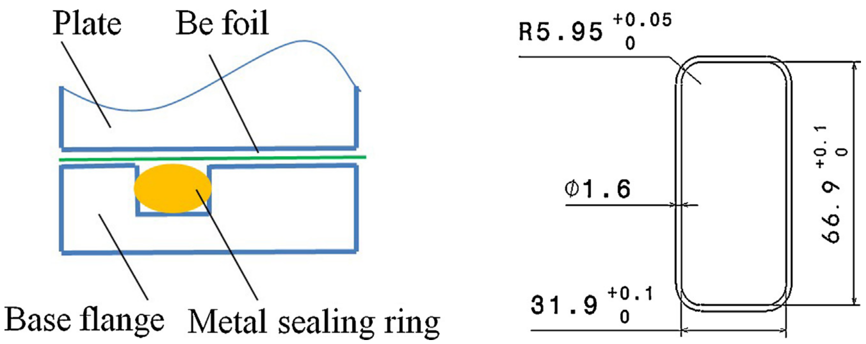

Fig. 6. Sketch of sealing structure and the metal sealing ring.

of the beryllium foil, the interface between the sealing ring and the bottom surface of the groove. In order to prevent the beryllium foil from crushing in the area where attaching and pressing the sealing ring, the sealing ring should have a small hardness and need small pretightening force.

Two types of metal sealing ring were applied and tested in the R&D process and satisfied results were achieved, one is hollow metal sealing ring with Ag coating and the other one is pure Ag sealing ring. The hollow metal sealing ring was manufactured by SS-316L pipe whose cross-section diameter is 1.58 mm with wall thickness of 0.254 mm. A 0.03 mm thickness of Ag was coated in the surface of the sealing ring which can refine the contact between the sealing ring and the sealing groove or the beryllium foil. The pure Ag sealing ring was produced by 99.8% pure silver whose Vickers hardness (HV) is about 58 (after annealing). The metal sealing rings were pressed by twelve bolts, and the connection force with 2000–3000 N/cm was enough for both of the sealing rings.

2.7.1. Basic consideration and verification of the beryllium window's structure safety

In addition to the high pressure that the beryllium foil would bear under accident events, radiation thermal and vibration are the other factors that would affect the structure stability of the beryllium window. Radiation damage in the beryllium window is much lower than 10^{-3} dpa for the full ITER-lifetime irradiation and this damage is negligible [11]. There are three types of thermal loads on the ITER RXC diagnostic during the D–D operation phase: nuclear heating by neutrons and gamma rays, the plasma radiation and heat conductivity through the flange from the port plug [11]. As the beryllium window installed in the outside of the port flange, the plasma radiation heat load are negligible. Referring the cooling and thermal analysis result of ITER port plug #1 in which the temperature distribution with nuclear heating applied, the temperature on the port flange is about 100 °C [12]. The FE model was created in ANSYS software, the temperature of 100 °C (inner camera) and 25 °C (outer camera) was applied to the end surfaces of the window, based on the neutronic analysis the nuclear heating in the beryllium window area is about 1×10^{-3} W/cm^3 [12,13], after the thermal analysis was finished the temperature distribution was transferred to the structural analysis model as thermal load, the bolt holes were fixed to simulate the bolted connection. By calculation, the maximum stress of the beryllium foil is 67.8 MPa (Fig. 7) which is much less than the design limitation (with yield stress of 207 MPa). Vibration of vacuum vessel will be transmitted to the window area and the level of vibration has not defined yet. But, based on the modal analysis, the window has large rigidity whose first-order natural frequency is more than 8000 Hz, which means that the resonance of the window can be avoided during ITER operation.

3. Sealing performance testing and verification

3.1. High temperature baking and vibration test

Baking affects the sealing performance of the sealing ring, especially for the mechanical clamped beryllium window. For the difference of thermal expansion coefficient of the SS-316L and the beryllium, minor air gap would be generated in the sealing interfaces when the window was cooled form high temperature to a low temperature, which can destroy the vacuum tight of the window. In the operation phase the temperature of the beryllium window is about 100 °C, while the window should be baked to 240 °C to outgas in the beginning of the experimental campaign. Baking tests of 240 °C (2 h) were carried out toward the two types of beryllium

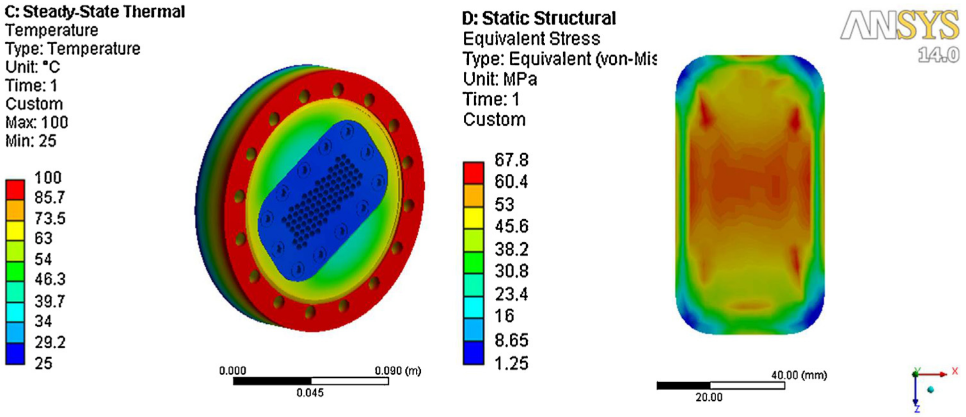

Fig. 7. Thermal and structural analysis of the beryllium window during operation.

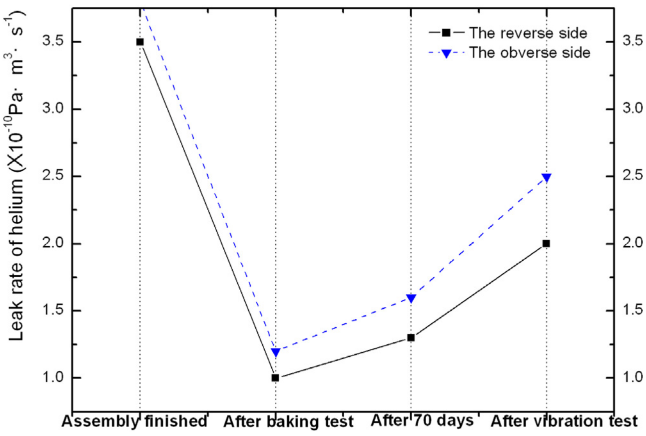

Fig. 8. Baking and vibration tests of mechanical clamped window.

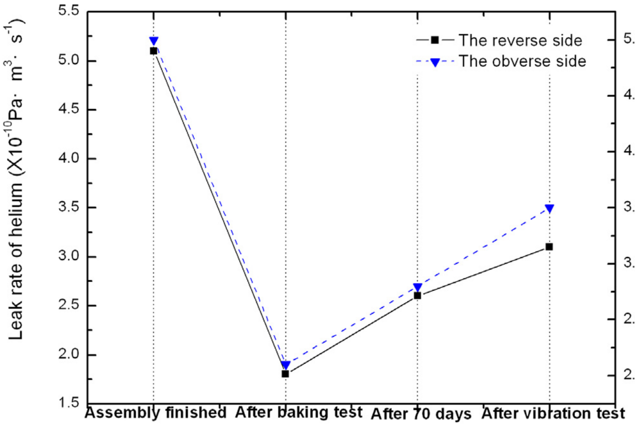

Fig. 9. Baking and vibration tests of diffusion bonded window.

windows. When beryllium windows are being shipped, vibration is inevitable and vibration could destroy the joint between beryllium and the window base, especially for the mechanical clamped one. Vibration tests of the beryllium windows on the simulation transportation vibration table with 3.3 Hz, 2 h were done to validate their safety during transportation stage. The changing of the windows' sealing performance after the above quality tests can be observed in the leakage test (one side of the beryllium window was connected to the vacuum pumping system of the leak detector, the other was exposed to the atmosphere) followed.

3.2. Strength and impact fatigue test

When the beryllium window used on ITER tokamak, it will isolate the vacuum of VV and the ITER RXC outer camera, which means that the forces on the two sides of the foil caused by gas pressure are almost zero. When accident event occurs, each side would have the possibility to expose to the atmosphere. Suffering the impacting pressure without broken or emerging large leakage points is essential to prevent the neutron contamination. The strength and impact fatigue tests can simulate the accident events of the vacuum of ITER tokamak to test the strength and also the fatigue properties of the beryllium windows. During the impact tests, one side of the beryllium window was exposed to air with pressure of 0.1 MPa, while the other side was pumped to vacuum rapidly with rotary vane pump (4 L/s), in which the impact pressure load was simulated so that the beryllium foil was impacted by the air pressure in a short time. After that, the leak rate of the window was checked. If the beryllium window turned to be broken or the leak rate of it exceeded the design requirement, the test would be stopped. Otherwise, the vacuum would be drained and the above process was repeated again.

3.3. Tests results and analysis

As Figs. 8 and 9 show, after baking tests, the leak rate of the two types windows decreased which may be caused by the refinement of the attaching between the beryllium foil and the Ag sealing ring or the support plate under 240 °C. After seventy days when the beryllium windows were manufactured, the leak rate of them increased slightly, however, seventy days are enough compared with the duration of ITER physics experimental campaign. Compared with the obverse sides the reverse sides showed a better sealing performance just because the bonding joints were compacted at that time.

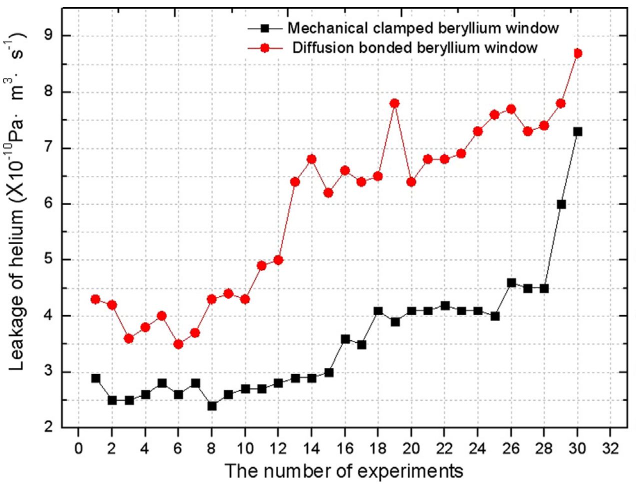

Fig. 10. Variation of leak rate of the two types windows during strength and impact fatigue test.

For the obverse sides of the windows were more vulnerable than the other sides, they were chosen as the study objects in the strength and fatigue tests whose results are shown in Fig. 10.

With the increase of the number of experiments, the leak rate of the two types of beryllium windows raised accordingly. After 20 times of impact fatigue experiments, the sealing performance of the diffusion bonded beryllium window no longer meets the design requirement (leak rate less than 6×10^{-10} Pa m^3 s^{-1}). And the number of impact fatigue experiments for the mechanical clamped one is 30, which means that the later one has better stability for use.

4. Conclusion

Beryllium window is the key component for the ITER RXC, whose function affects not only the stability of the RXC diagnostic but also the nuclear safety of the environment. By keeping the balance, the safety and the sensitivity of diagnostic device, 80 μm beryllium foil was used in the window, which has the threshold of X-ray for 1.24 keV. In the R&D phase, two types of beryllium windows were designed, manufactured and tested. The use of diffusion bonding method and the application of the intermediate layer minimized the negative effect to the bonding joint caused by the thermal stress. Dividing the big aperture into many small ones is a useful way to limit the maximum stress on the foil. Vacuum diffusion bonding and EB welding were applied to bond the beryllium foil to the support plate and the support plate to the base flange. On the mechanical clamped beryllium window, metal sealing ring was used to realize the vacuum isolation for its insensitivity of high temperature and high dosage of neutron radiation. Hollow metal sealing ring made by SS-316L with 0.03 mm thickness Ag coating and silver sealing ring can satisfy the operating requirement, and the later one is less sensitive to the machining accuracy which was selected finally. Honeycomb-like supports can strengthen the beryllium foil and guarantee the beryllium window's safety when being exposed to high pressure. A series of qualification tests were carried out to validate the stability of the window's sealing performance which showed that 240 °C baking and shipping did not cause failure of the sealing joints and the reverse sides showed better sealing performance compared with the obverse sides. In the strength and impact fatigue tests, it showed that the two types of beryllium windows could sustain 0.1 MPa impacting pressure load for many times and the mechanical clamped one was more stable.

Acknowledgements

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